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Mean Diurnal Variation of the Topside Ionosphere at Mid-Latitudes

G.P.

S. J. BAUER AND L. J. BLUMLE

N 64 32640

Goddard Space Flight Center, Greenbelt, Maryland

32640

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Abstract. About 500 ionograms obtained with the Alouette satellite have been used to construct the mean diurnal variation of the mid-latitude topside ionosphere. Since this diurnal variation is based on observations from October to December 1962, quasi-seasonal effects had to be removed. The data are presented in the form of electron-density contours at fixed altitudes for two latitude ranges, 35°N–40°N and 40°N–45°N. These ranges, which are approximately separated at the 75°W meridian by the 70° magnetic dip line, show remarkable differences in the detailed behavior of electron density as a function of time and altitude. From the scale heights of these mean distributions it is apparent that there is absence of thermal equilibrium, at least during the day, and that light ionic constituents become important in the altitude region from 500 to 1000 km, especially during the night. There is also the suggestion of latitude gradients in the electron temperature and mean ionic mass.

Author

INTRODUCTION

Before the launching of the Canadian topside sounder satellite Alouette, our knowledge of the vertical structure of the ionosphere above the F_2 peak was based on occasional rocket flights and incoherent radar backscatter observations from the ground, both of which are limited to specific locations. The topside sounder satellite provided for the first time a tool for the study of the topside ionosphere and its variation with latitude and time. Since the topside sounder operates only on command, observations are restricted to times when the satellite is within appropriate range of a telemetry and command station. We have made use of soundings of the topside ionosphere taken while the satellite was within range of the NASA telemetry station at Blossom Point, Maryland, from which the latitude coverage obtainable is between 20°N and 55°N. We have concentrated on the study of ionograms obtained at mid-latitudes (35°N to 45°N), for which our data were most complete. As the result of the orbital characteristics of the Alouette satellite, and combining north- and southward passes, about 3 months is required to obtain a complete diurnal variation of the ionospheric parameters. This paper presents the mean diurnal behavior of the mid-latitude topside ionosphere for the 3-month period from October to December 1962.

DIURNAL VARIATION OF ELECTRON DENSITY AT CONSTANT ALTITUDES

About 500 ionograms taken on magnetically quiet days during the first 3 months of Alouette's operation and covering the latitude range from 30°N to 50°N (and longitudes 50°W to 100°W) were selected for the present study. They were converted to electron-density profiles by means of the exponential lamination method described by *Fitzenreiter and Blumle* [1964]. For the study of the diurnal behavior of the topside ionosphere, a presentation in terms of electron density at constant altitudes was chosen. In this way a mean behavior could best be defined from the large number of data points. It became apparent that, because of the latitude variation of the topside ionosphere, latitude ranges of not more than 5° latitude should be used; otherwise, the spread in the electron-density data points at constant altitudes would often be greater than the separation of electron-density contours at successive 100-km altitude increments. Since below 35°N and above 45°N the data available were not sufficient to define a complete diurnal variation, only the two latitude ranges from 35°N to 40°N and from 40° to 45°N will be presented in this paper.

The 'mean' contours of electron density at 100-km height intervals are based on individual data points; the maximum spread of individual

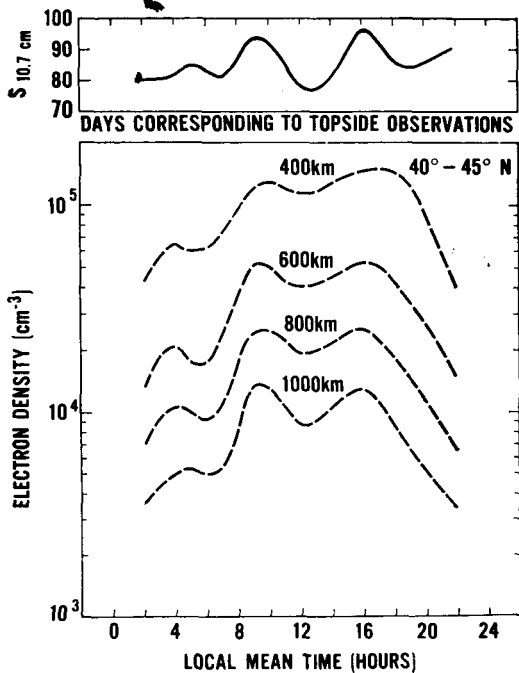


Fig. 1. Mean diurnal variation of electron density at constant altitudes based on actual data points and flux of 10.7-cm solar radiation (in units of 10^{-22} w/m²/cps) at times corresponding to the ionospheric measurements, indicating 'quasi-seasonal' effects (27-day cycle).

data points around the density contours at fixed heights is of the order of $\pm 25\%$. Figure 1 shows an example of such mean contours every 200 km up to the satellite altitude for the latitude range 40°N to 45°N . It can be seen that these mean contours have some oscillations superimposed which need not represent actual diurnal behavior, since the entire 'diurnal' variation is based on 3 months of data. Thus, the mean contours presented in Figure 1 will also include quasi-seasonal effects, e.g., the 27-day cycle.

This becomes quite apparent, if the flux of the solar 10.7-cm radiation, $S_{10.7}$, which is an indicator of solar activity, is plotted for the days corresponding to the individual data points for electron density at the indicated local times. The smoothed variation of $S_{10.7}$ is plotted in the top part of Figure 1, and it is evident that the electron density at fixed altitudes behaves in a similar fashion. At first it may seem surprising that the topside electron density should be closely related to the 10.7-cm flux from the sun,

since there is no obvious correlation of this parameter with the density at the F_2 peak, or below. However, it should be realized that at lower altitudes, where production and loss of ionization play a predominant role, the detailed correlation of electron density with short-term solar variations as indicated by the 10.7-cm flux may be obscured by the fact that both production and loss are affected by the variation of the appropriate neutral constituents and are thus effectively canceled out. At altitudes above the F_2 peak, where the distribution is controlled by diffusion, and thus by the scale height, this effect may appear more directly, since the scale height and temperature are known to be directly correlated with the 10.7-cm flux.

Correspondingly, the seasonal effect superimposed on the diurnal variation was removed, using the behavior of the 10.7-cm solar flux as an indicator and normalizing the mean diurnal variation to a condition of $S_{10.7} = 85 \times 10^{-22}$ w/m²/cps. This was accomplished by making a percentage correction of the electron-density contours appropriate to the variation of $S_{10.7}$.

The mean diurnal variation of electron density at fixed altitudes, corrected for quasi-seasonal effects, is shown in Figure 2 for the latitude range 35°N to 40°N and in Figure 3

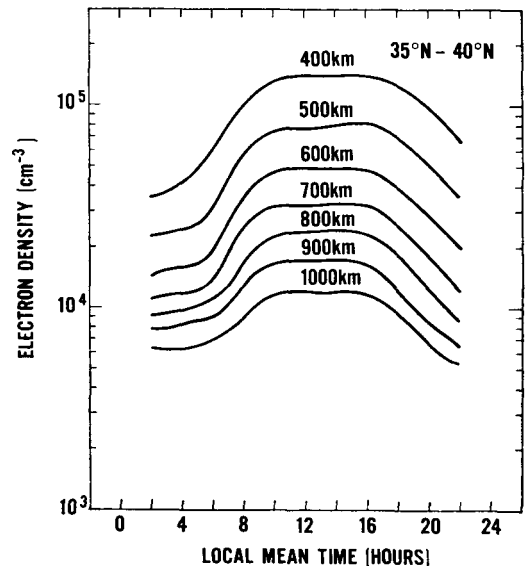


Fig. 2. Diurnal variation of electron density at constant altitudes for the latitude range 35°N to 40°N (corrected for quasi-seasonal effects).

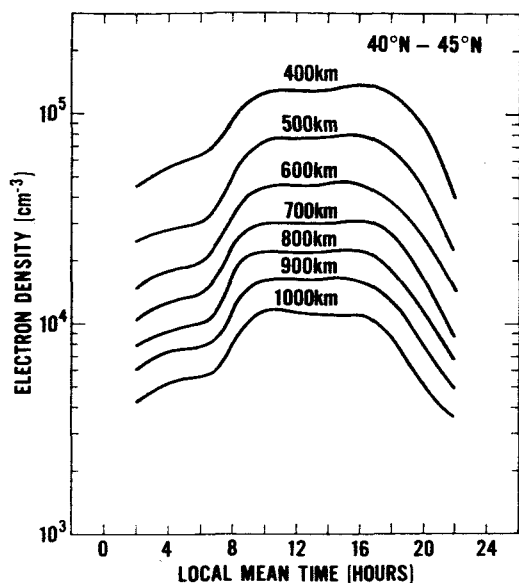


Fig. 3. Diurnal variation of electron density at constant altitudes for the latitude range 40°N to 45°N (corrected for quasi-seasonal effects).

for 40°N to 45°N . Whereas the daytime values for the two latitude ranges are virtually identical, the electron-density contours show a quite different behavior during the rest of the day. (The fact that there are no data between 2200 and 2400 LMT is the result of poor performance of the topside sounder during these night hours as the result of leakage of terrestrial noise, which causes blocking of the receiver [Atkins and Chapman, 1963].)

In comparing the behavior of the mean diurnal variation at the two latitude ranges, which can be termed in the geographical sense as *mid-latitudes*, it must be kept in mind that magnetically this latitude range at the 75°W meridian is already representative of rather high dip angles; e.g., at 39°N , 75°W , the magnetic dip is $I = 70^{\circ}$. It appears that this dip represents something of a boundary between normal and auroral type of ionosphere. This is also evidenced in the behavior of spread F as shown in the paper by Calvert and Schmid [1964], and thus is possibly also indicative of the role of corpuscular effects in the ionosphere (cf. Mariani [1963]). Similar conclusions have been drawn on the basis of a comprehensive study of the behavior of the bottomside ionosphere [Wright, 1962].

The different behavior of the topside in the two latitude ranges, which are only 5° apart yet include the 'dip boundary,' can best be illustrated by comparing the amplitude of the diurnal variation at selected fixed heights at the 35°N to 40°N latitude range with that at 40°N to 45°N . This is shown in Figure 4, where the normalized electron density, i.e., the ratio of electron density at a particular local time to the minimum value of electron density at selected altitudes, is plotted as a function of local mean time for both latitude ranges. It is obvious that the diurnal amplitude is decreasing with altitude for the latitudes 35°N to 40°N , whereas for 40°N to 45°N the diurnal amplitude is virtually independent of altitude. Furthermore, the absolute value of the amplitude at 400 km is higher at 35°N to 40°N than at 40°N to 45°N .

The variation of the diurnal amplitude at latitudes 35°N to 40°N as a function of altitude is qualitatively what is expected from theoretical considerations [Gliddon and Kendall, 1962], but the actual decrease with altitude of the ratio of maximum to minimum density from a value of 4 at 400 km to a value of 2.3 at 1000 km is still much slower than theoretical estimates. It should be noted, however, that, although the theoretical model of the F_2 region by Gliddon and Kendall is based on the solution of the time-dependent continuity equation, it is not strictly applicable to the topside ionosphere because it assumes an isothermal atmosphere whose temperature also does not show a diurnal variation. It is evident from Figure 4 that the

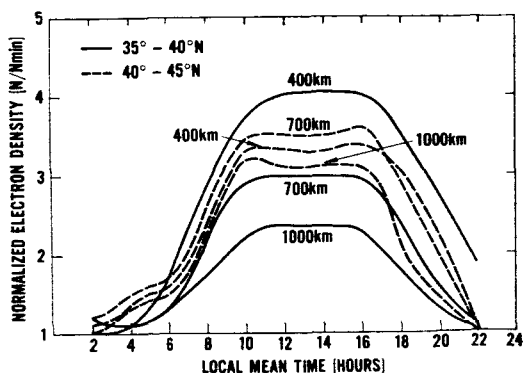


Fig. 4. Time variation of normalized electron density at fixed altitudes illustrating the variation with altitude of the diurnal amplitude for the two latitude ranges.

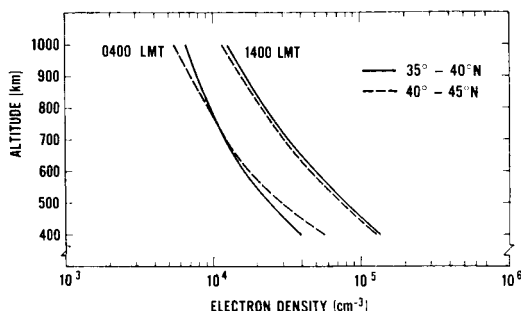


Fig. 5. 'Mean' electron-density profiles of the mid-latitude topside ionosphere corresponding to times of the diurnal temperature maximum (1400 LMT) and minimum (0400 LMT).

diurnal behavior of the topside ionosphere, especially at latitudes greater than 40°N , is quite different from simple model concepts. The reason for the discrepancies is obviously the importance of a variable scale height as the result of diurnal variation of temperature, absence of thermal equilibrium between electrons and ions, and a varying ion composition.

The above conclusion, that a variable scale height is indeed responsible for the altitude behavior of the diurnal amplitude of electron density at fixed levels, is more readily apparent in 'mean' vertical profiles of electron density (derived from cross sections of the electron density contours at fixed heights, as shown in Figures 2 and 3). Figure 5 shows such mean profiles for the two latitude ranges at 0400 and 1400 LMT, the times corresponding to the diurnal minimum and maximum of the atmospheric temperature. The problems concerning a variable scale height of the topside ionosphere and the implications from the observations presented here are discussed in the following section.

DERIVED QUANTITIES:

SCALE HEIGHT, ELECTRON TEMPERATURE, AND ION COMPOSITION

The spacing of electron-density contours at fixed altitudes shown in Figures 2 and 3 is a measure of the scale height of the electron-ion gas. It is well known that in the topside ionosphere this scale height is given by

$$H' = \frac{k(T_e + T_i)}{m_+ g} = \left[-\frac{1}{N} \frac{\partial N}{\partial z} \right]^{-1}$$

where k is Boltzmann's constant, T_e and T_i are the electron and ion temperature, respectively, m_+ is the mean ionic mass, and g is the acceleration of gravity. From the diurnal variation of the mean electron-density contours it is thus also possible to infer the diurnal variation of the scale height.

Figure 6 shows the scale height H' at an altitude of 500 km for the two latitude ranges under consideration as a function of local mean time. In addition, a scale is given for the effective charged particle temperature $(T_e + T_i)/2$, assuming a mean ionic mass $m_+ = 16$. That assumption may be justifiable at the given altitude, at least during the daytime. In examining the variation of H' as a function of local time it must be remembered that this variation is the result of variation in *electron and ion temperature and in ion composition*. Referring to the temperature scale, it is obvious that the effective charged particle temperature is in excess of the neutral gas temperature T_n for the given 3-month period, when T_n was about 1000°K during the day and about 700°K at night (cf. Nicolet [1963]). Thus, it is quite evident that thermal equilibrium is absent, at least during the day (when $m_+ = 16$ may be a reasonably good assumption). If we assume that $T_i = T_n \approx 1000^\circ$, the electron temperature T_e is of the order of 2000°K during most of the day with an even higher value around 0900 LMT. (If m_+ is less than 16, then T_e is reduced propor-

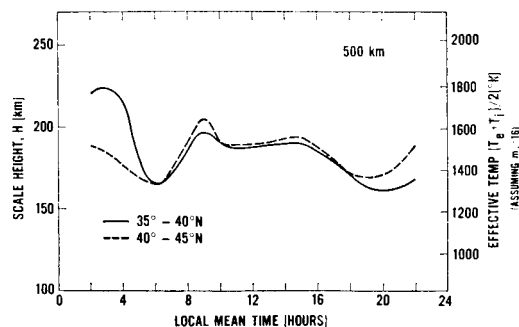


Fig. 6. Electron-ion scale heights at 500 km for the two mid-latitude ranges as a function of local mean time, together with corresponding scale for the effective charged-particle temperature $(T_e + T_i)/2$, assuming $m_+ = 16$. The interpretation of scale heights in terms of electron temperature T_e and mean ionic mass m_+ is discussed in the text.

tionately; thus, the above value represents an upper limit.)

It is interesting to note that actual measurements of T_e near the F_2 peak for the same latitude range obtained from Blossom Point telemetry readouts of the S-6 aeronomy satellite [Brace *et al.*, 1964] during spring and summer of 1963 are in excellent agreement with our inferred electron temperatures. Even the maximum at 0900 LMT and the subsequent plateau in the electron temperature appear in both data. Thus, we are confident that our assumptions are reasonable.

Furthermore, there is the suggestion of a latitude gradient in the scale height during the day when we are able to infer electron temperature. The electron temperature appears to be higher at latitudes greater than 40°N than below that, a conclusion again in agreement with the actual measurements of electron temperature by Brace *et al.* [1964]. During the early morning hours (0200–0500 LMT) the electron-ion scale height H' is higher than, or at least comparable to, the daytime values. This cannot be explained in terms of temperature, since there is good reason to believe that atmospheric heating is lower at night (assuming that the main heat source is solar EUV with a possibly constant, corpuscular component superimposed on it). The more plausible explanation is that the large scale height during this time period is the result of a change in the ion composition, indicating the presence of the lighter ionic constituents He⁺ and H⁺. The latitudinal gradient in scale height is reversed during this time period, implying that, in terms of ion composition, the preponderance of the light ions is weighted toward lower latitudes.

This inference finds support in observations

of ion composition on the Ariel satellite [Bowen *et al.*, 1964]. If such a latitude gradient of ion composition does indeed exist even during the day, the latitude gradient in electron temperature would be even larger than that apparent from the daytime scale heights for the two latitude ranges. Ion composition, or rather the mean ionic mass m_+ at 500 km, can be inferred from the scale height if assumptions are made about the electron and ion temperatures. Assuming, first, that thermal equilibrium prevails during the night, then, at 0400 LMT (corresponding to the diurnal temperature minimum), $T_e = T_i = T_n \approx 700^\circ\text{K}$ for the time period under consideration. Accordingly, the mean ionic mass at 500 km is $m_+ \approx 8$ amu at latitudes 40°N to 45°N and $m_+ \approx 7$ amu at latitudes 35°N to 40°N. The trend seems to be reversed in the late evening hours, when the scale heights are greater at higher latitudes than at the lower latitudes. However, the assumption of thermal equilibrium may not hold even during the night, since electron temperatures $T_e \approx 1000^\circ\text{K}$ have been observed at nighttime [Brace *et al.*, 1964] which are in excess of the estimated neutral gas temperature for the corresponding time period. In this case the mean ionic masses quoted above would be increased to $m_+ \approx 10$ amu (40°N to 45°N) and $m_+ \approx 8$ amu (35°N to 40°N). In any event, obviously, the light ionic constituents must become important during the night even at altitudes as low as 500 km.

It is interesting to compare the scale heights at 500 km with the scale heights at 800 km derived in the same fashion. During the night (0400 LMT) the ratio of the scale heights $H'(800)/H'(500) \approx 2.5$ at 35°N to 40°N and about 2.1 at 40°N to 45°N, whereas during the

TABLE 1. Inferred Mean Ionic Mass m_+

Altitude, km	$\frac{T_e}{T_{i,n}}$	0400 LMT		1400 LMT	
		35°–40°N	40°–45°N	35°–40°N	40°–45°N
500	1	~7 amu	~8 amu
	>1	~8 amu	~10 amu	(16 amu)	(16 amu)
800	1	~3 amu	~4 amu	~6 amu	~7 amu
	>1	~3.5 amu	~5 amu	~9 amu	~11 amu

day (1400 LMT) this ratio is about 1.9 at the lower and 1.6 at the higher latitudes. Taking into account the altitude variation of the acceleration of gravity g , and making the same assumptions as before about the electron and ion temperature, it is again possible to infer the mean ionic mass at 800 km. Table 1 summarizes the inferred mean ionic mass at the two latitude ranges, considered here.

It is obvious from Table 1 that light ionic constituents (He^+ , H^+) must become important at 800 km even during the day; during the night H^+ must be an important constituent, at least at the lower latitudes. To infer the relative abundance of ionic constituents becomes somewhat hazardous, since the additional assumption would have to be made that the light ions are in diffusive equilibrium, an assumption that may not be justified even at altitudes as high as 700 km [Bauer, 1964]. Thus, the mean ionic mass m_+ can only be used as an *indicator* of the presence of ions lighter than O^+ , and no reliable and unique data on the abundance of the individual light ions can be inferred from the electron-ion scale height under the present circumstances.

CONCLUSIONS

Although it is not possible by means of satellite observations to obtain directly the true diurnal variation of the topside ionosphere, a *mean* diurnal variation can, with proper precautions, be constructed from daily observations over an extended period of time. The mean diurnal variation of the topside ionosphere at mid-latitudes based on Alouette observations from October to December 1962 exhibits the following features:

1. There is a significant difference in the diurnal behavior between the latitude ranges 35°N to 40°N and 40°N to 45°N , the boundary of which appears to be associated with the 70° magnetic dip line.

2. The vertical cross section of the topside

ionosphere is indicative of an electron-ion scale height *variable* with altitude, latitude, and time.

3. There is definite evidence of absence of thermal equilibrium, at least during the daytime, with $T_e/T_{i,m} \approx 2$ at 500 km.

4. The mean ionic mass inferred from the scale height indicates that the light ionic constituents He^+ and H^+ are already of importance during the day at 800 km and during the night at an altitude as low as 500 km.

5. There is some indication of opposite latitude gradients in electron temperature and mean ionic mass, the electron temperature increasing with latitude.

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